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HOURLY FREQUENCY AND INTENSITY OF RAINFALL AT NEW ORLEANS, LA.

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By W. F. McDONALD

[Weather Bureau Office, New Orleans, La., December 18, 1928]

Studies of rainfall frequency and intensity have been made at various places, based upon the precipitation automatically recorded at regular Weather Bureau stations.[1] Good records of hourly precipitation are, at most places, confined to the years since the late nineties, but it seems that there is not in print any study of hourly rainfall extending over as many as 30 years of record. Fairly complete hourly data for the New Orleans station for 30 years, 1898 to and including 1927, have been obtained by transcribing the amounts prior to 1905, shown by the original sheets now on file at this station.

The means of registration has been the self-recording rain gauge of the tipping bucket type; which gives the time distribution of rainfall measured in hundredths of an inch. The time intervals used for tabulations are the clock hours, with the recorded amounts conforming to the fixed hour lines marking standard time on the record sheets. None but the heaviest rainfalls are treated in Weather Bureau records, with reference to the time of occurrence of given intensities rather than upon the fixed clock hours.

This study treats the record in two aspects—frequency and intensity. Every hour with a precipitation record has been counted, to produce hourly, monthly, and annual totals for the 30 years.

In considering these hourly precipitation records as matter for statistical comparison it is well to consider several limitations. The first is that the hourly entries in the records prepared, as they must be, with reference to the 24 clock hours, are really random samples of precipitation intensity. Precipitation is irregular in time, particularly in the area which is represented by the New Orleans records. Any brief shower will produce an hour record, whether the duration of rainfall be for a few minutes or for a full hour or more. Precipitation extending a little longer than 60 minutes can and often does produce a record in three separate clock hours, as it may begin near the close of the first hour, extend through the next, and end shortly after the opening of the third hour. The summation of the hour entries for a period of years therefore runs to a total considerably greater than the true duration of rainfall, this being especially true for the region of the Gulf coast, where rainfalls are commonly of short duration.

While from a purely practical point of view, concerned with interference with outdoor work, transportation, sales, etc., the hours with *measurable rain* are admittedly the principal end of study, there is great interest, from the meteorological point of view, in including also the hours with any rainfall whatever; that is, hours in which only traces of rain are recorded. The fact that precipitation even in insignificant amount is occurring, is important as showing the existence of that combination of circumstances which may be briefly designated as the "rain condition." In summer especially traces often actually represent the occurrence of measurable and at times of heavy showers in the near vicinity, but showers of such limited compass that only the outer edge of the rainfall area affects the recording station.

Table 1 gives for the 30 years 1898–1927 the hourly and monthly sums of (*a*) hours with only a trace of precipitation, (*b*) hours with 0.01 or more inch of rainfall recorded within the hour, and (*c*) the sum of (*a*) and (*b*). The last figure may be properly considered the truer measure of frequency of the "rain condition."

It is true that because of the fact that traces of rain are not automatically recorded, these records are more subject to personal errors of observation. Light rainfalls in middle night hours are certainly not fully recorded, as the following consideration of the data will confirm: The grand total of all hours with traces of rain is only slightly diminished by those failures of record due to the lack of observations during night hours. Roughly, the monthly total of hours with traces of rain is 65 to 75 per cent of the total with measurable rainfall. Many of the hours between midnight and 4 a. m. have a much smaller proportion of recorded traces, running as low as one-third in some instances, and below the average proportion much more frequently than during the other hours of the day. This appears to indicate the loss of some records of traces of rain during those middle night hours. Moreover, the hours around 7 a. m., noon, and 7 p. m. appear to carry a somewhat larger than average proportion of traces to measurable rains; this leads to the suspicion that those times of day have been more accurately observed by reason of their being times when the observers are likely to be out of doors and therefore able to secure personal observation of very slight amounts of rainfall which might otherwise have escaped notice.

[1] Excellent studies of rainfall frequency and intensity have been published by Tannehill for the Texas coast, as follows:

Tannehill, I. R.: Wind Velocity and Rain Frequency on the South Texas Coast; Mo. Weather Rev., September, 1921, 49:498–499.

Tannehill, I. R.: Frequency Distributions of Daily and Hourly Amounts of Rainfall at Galveston, Tex.; Mo. Weather Rev., January, 1923, 51:11–14.

Hourly frequency studies for Chicago (1902–1911), are a part of the discussion of the climate of Chicago, in the following:

Cox, H. J., & Armington, J. H: The Weather and Climate of Chicago; pp. 205–208. University of Chicago Press. 1914.

Fassig, O. L. Report on the Climate and Weather of Baltimore and Vicinity. Baltimore. 1907. (Maryland Weather Service, v. 2, pp. 167–170.)

See also a brief discussion relating to foreign stations in J. Hann's Lehrbuch der Meteorologie, 4th ed., Leipzig, 1926, pp. 353–4.

TABLE 1.—*Total number hours with rain at New Orleans, La. (1898–1927, inclusive)*

Month	Class of data counted	Hours ending— A. M. 1	2	3	4	5	6	7	8	9	10	11	Noon 12	P. M. 1	2	3	4	5	6	7	8	9	10	11	Mid. 12	Total
January	Traces ....A	39	42	36	44	37	39	56	63	50	47	32	45	63	53	53	47	38	50	42	60	55	39	42	44	1,116
	0.01 or more ....B	50	48	55	59	63	69	57	49	45	42	54	49	64	59	64	64	67	60	65	50	52	51	42	44	1,322
	Sum, a+b.....C	89	90	91	103	100	108	113	112	95	89	86	94	127	112	117	111	105	110	107	110	107	90	84	88	2,438
February	Traces ....A	28	24	22	35	40	38	42	53	44	36	33	44	56	41	41	37	40	38	40	51	47	41	30	38	939
	0.01 or more ....B	53	52	51	49	52	55	49	50	51	51	49	49	49	51	43	46	52	62	58	52	49	50	51	39	1,213
	Sum, a+b.....C	81	76	73	84	92	93	91	103	95	87	82	93	105	92	84	83	92	100	98	103	96	91	81	77	2,152
March	Traces ....A	21	20	23	23	29	37	34	50	36	34	37	38	49	50	45	42	53	43	38	37	39	35	32	18	863
	0.01 or more ....B	39	43	41	44	41	49	54	46	46	41	46	50	58	52	59	56	57	53	53	54	40	36	34	36	1,128
	Sum, a+b.....C	60	63	64	67	70	86	88	96	82	75	83	88	107	102	104	98	110	96	91	91	79	71	66	54	1,991
April	Traces ....A	7	8	12	12	15	24	32	44	32	22	23	29	31	29	29	24	33	27	32	29	21	13	16	12	556
	0.01 or more ....B	36	40	29	32	30	27	31	36	35	34	34	36	35	43	45	46	37	38	36	35	34	36	35	30	850
	Sum, a+b.....C	43	48	41	44	45	51	63	80	67	56	57	65	66	72	74	70	70	65	68	64	55	49	51	42	1,406
May	Traces ....A	8	7	12	14	17	18	26	30	18	14	28	30	38	37	36	23	30	33	27	25	21	19	17	11	539
	0.01 or more ....B	26	28	29	31	34	32	36	26	33	44	40	51	48	53	52	40	36	39	44	34	29	30	24	22	861
	Sum, a+b.....C	34	35	41	45	51	50	62	56	51	58	68	81	86	90	88	63	66	72	71	59	50	49	41	33	1,400
June	Traces ....A	13	10	12	12	17	16	14	22	34	36	38	57	68	70	49	53	43	37	37	30	23	16	18	13	738
	0.01 or more ....B	15	16	13	18	25	23	24	20	29	50	62	88	101	94	98	93	78	59	33	31	27	17	19	13	1,046
	Sum, a+b.....C	28	26	25	30	42	39	38	42	63	86	100	145	169	164	147	146	121	96	70	61	50	33	37	26	1,784
July	Traces ....A	8	6	9	13	12	23	35	34	28	48	47	75	97	70	73	64	52	60	55	33	25	22	17	11	917
	0.01 or more ....B	10	8	15	26	29	31	34	32	48	54	82	104	124	126	114	108	77	70	45	35	26	23	18	13	1,252
	Sum, a+b.....C	18	14	24	39	41	54	69	66	76	102	129	179	221	196	187	172	129	130	100	68	51	45	35	24	2,169
August	Traces ....A	7	7	12	15	15	10	24	26	21	24	42	64	87	76	69	65	55	45	55	35	27	12	16	8	817
	0.01 or more ....B	13	13	15	22	22	17	18	17	31	44	69	94	111	128	105	92	86	72	48	28	23	22	13	15	1,118
	Sum, a+b.....C	20	20	27	37	37	27	42	43	52	68	111	158	198	204	174	157	141	117	103	63	50	34	29	23	1,935
September	Traces ....A	9	18	14	11	16	20	20	34	24	28	47	50	64	45	50	53	56	37	39	33	30	24	18	17	757
	0.01 or more ....B	28	31	32	32	34	38	43	39	36	42	57	77	84	112	101	73	68	59	45	29	27	24	25	23	1,159
	Sum, a+b.....C	37	49	46	43	50	58	63	73	60	70	104	127	148	157	151	126	124	96	84	62	57	48	43	40	1,916
October	Traces ....A	15	10	16	18	25	28	24	41	31	25	25	37	42	30	31	20	28	31	26	27	22	14	9	9	584
	0.01 or more ....B	24	31	29	27	29	26	36	24	33	37	37	41	61	55	55	52	51	45	36	27	20	20	27	26	849
	Sum, a+b.....C	39	41	45	45	54	54	60	65	64	62	62	78	103	85	86	72	79	76	62	54	42	34	36	35	1,433
November	Traces ....A	10	21	24	19	23	21	31	36	25	31	31	28	39	20	23	28	29	35	21	26	24	36	25	10	616
	0.01 or more ....B	30	36	27	30	29	40	41	36	37	33	32	40	35	43	37	42	35	26	36	36	35	36	32	39	843
	Sum, a+b.....C	40	57	51	49	52	61	72	72	62	64	63	68	74	63	60	70	64	61	57	62	59	72	57	49	1,459
December	Traces ....A	36	42	32	51	46	48	49	57	59	59	49	56	67	51	56	48	44	58	61	57	54	49	60	40	1,229
	0.01 or more ....B	65	69	77	69	68	72	76	75	66	68	66	65	70	73	70	72	79	65	66	60	65	72	68	65	1,665
	Sum, a+b.....C	101	111	109	120	114	120	125	132	125	127	115	121	137	124	126	120	123	123	127	117	123	121	128	105	2,894

Whatever may be the true weight of such apparent inaccuracies, the summation of the records of slight rainfalls adds in an important manner to the records of automatically measured rain, and in the main conforms well with and nicely supplements the count of the measurable records.

In going beyond this point to a comparison of the records in different months, we meet a second limitation which must be considered in using the raw data carried in Table 1. The difficulty here, as in the first case, grows out of the necessity for keeping records in artificial brackets, in this instance the varying lengths of the calendar months. Before the hourly or monthly totals for 28, 29, 30, and 31 day months can be accurately compared, some form of correction to secure uniformity must be applied. This is most simply cared for by reducing the number of rainfall hours to a percentage of the total time involved in any grouping. For example, there were 2,894 hours with precipitation, in December. The total amount of time in that month for 30 years is 22,320 hours, and precipitation of a trace or more therefore occurred in 13 per cent of the hours in December. Likewise the 30 years showed 1,213 hours in February within which rainfall of 0.01 inch or more was recorded; this was 6 per cent of the total, 20,304 hours, in that month for the whole number of years.

The count for each individual hour of the day, by months for the 30-year record, was similarly reduced to a percentage of the total number of hours of that name in the month. This base total to which percentages were referred varies from the sum, 846 in February, to 900 for any 30-day month, and 930 for 31-day months. Hourly percentage frequencies for measurable rains, given as round percentages, are shown in Table 2. It was not considered desirable to reduce the hourly records of traces of rain to a percentage basis.

TABLE 2.—*Frequency of occurrence of **measurable** rain in each hour, expressed as a percentage ratio of rainy hours to total number of same name in the month (New Orleans, La., 1898–1927, inclusive)*

Month	Hour ending—																							
	A. M.											Noon 12	P. M.											Mid. 12
	1	2	3	4	5	6	7	8	9	10	11		1	2	3	4	5	6	7	8	9	10	11	
January	5	5	6	6	7	7	6	5	5	5	6	5	7	6	7	7	7	6	7	5	6	6	5	5
February	6	6	6	6	6	7	6	6	6	6	6	6	6	6	5	6	6	7	7	6	6	6	6	5
March	4	5	4	5	4	5	6	5	5	4	5	5	6	6	6	6	6	6	6	6	4	4	4	4
April	4	4	3	4	3	3	3	4	4	4	4	4	4	5	5	5	4	4	4	4	4	4	4	3
May	3	3	3	3	4	3	4	3	4	5	4	5	5	6	6	4	4	4	5	4	3	3	3	2
June	2	2	1	2	3	3	3	2	3	6	7	10	11	10	11	10	9	7	4	3	3	2	2	1
July	1	1	2	3	3	3	4	3	5	6	9	11	13	14	12	12	8	8	5	4	3	2	2	1
August	1	1	2	2	2	2	2	2	3	5	7	10	12	14	11	10	9	8	5	3	2	2	1	2
September	3	3	4	4	4	4	5	4	4	5	6	9	9	12	11	8	8	7	5	3	3	3	3	3
October	3	3	3	3	3	3	4	3	4	4	4	4	7	6	6	6	6	5	4	3	2	2	3	3
November	3	4	3	3	3	4	5	4	4	4	4	4	4	5	4	5	4	3	4	4	4	4	4	4
December	7	7	8	7	7	8	8	8	7	7	7	7	8	8	8	8	8	7	7	6	7	8	7	7

Coberly's previous paper on this subject (Monthly Weather Review; September, 1914) presented a simple count of frequency of hourly rainfall records of 0.01 inch or more for the nine years, 1905 to 1913, inclusive. No effort was made by Coberly to effect strict comparability of his statistics for the various months. Examination of his data shows that August had markedly fewer hours with rain than did either July or September, although the normal rainfall amount is higher in August than in September, and there is no evident reason for thinking that the prevailing convectional type of rainfall should be less frequent in August than in adjacent months. It was, in fact, this unexpected discrepancy that led to the present study in an effort to arrive at the true frequency by consideration of a longer term of records.

Using the 30 years, 1898 to 1927, both inclusive, gives a body of data which by the length of record covered may be supposed to be more free from the accidental errors resultant from deficient sampling. However, it will be seen in Table 1 that August still shows a slightly lower total of hours (1,118) with measurable rain than does September (with 1,159), although the total of *all* hours including traces is slightly larger for August.

The distribution of measurable rainfall throughout the 24 hours of the day, by months, is represented in Figure 1, in which the percentage frequency of occurrence for each hour, as carried in Table 2, is depicted by radial distance in a circle providing place for each hour in the day. Rainfalls for the hours 6 p. m. to 6 a. m. have, for convenience, been distinguished from those of the other half of the day by distinctive shadings. It will be seen that winter rains are well distributed around all hours of the day. Extreme distortion of the distribution is characteristic of the hot months, when only a minor fraction of measurable rainfalls is recorded between 7 p. m. and 9 a. m.

The rainiest hour of the year at New Orleans, judged by the sum of traces and measurable rains, is the hour from noon to 1 p. m. in July (Table 1) when rain conditions enter the record on about one day in four. The hours between 1 and 2 p. m. in July and between noon and 2 p. m. in August show a frequency of the rain condition nearly as great as in the hour first named. Measurable amounts are most frequently recorded between 1 and 2 p. m. in August, and nearly as often in the same hour in July.

The driest hour of the year is between 1 and 2 a. m., in July, when frequency of the rain condition (including traces) is less than 2 per cent. Frequencies of only 1 per cent for measurable rains are recorded in several of the early morning hours in June, July, and August, when measurable rains are at minimum frequency.

The bias of hourly distribution of rainfall towards the warmer time of the day marks the summer thundershower type of precipitation, which reaches its highest perfection in August, but which is distinctly dominant from May through October, and shows its beginnings in April. The lack of other types of rainfall in August probably accounts for the slight comparative reduction

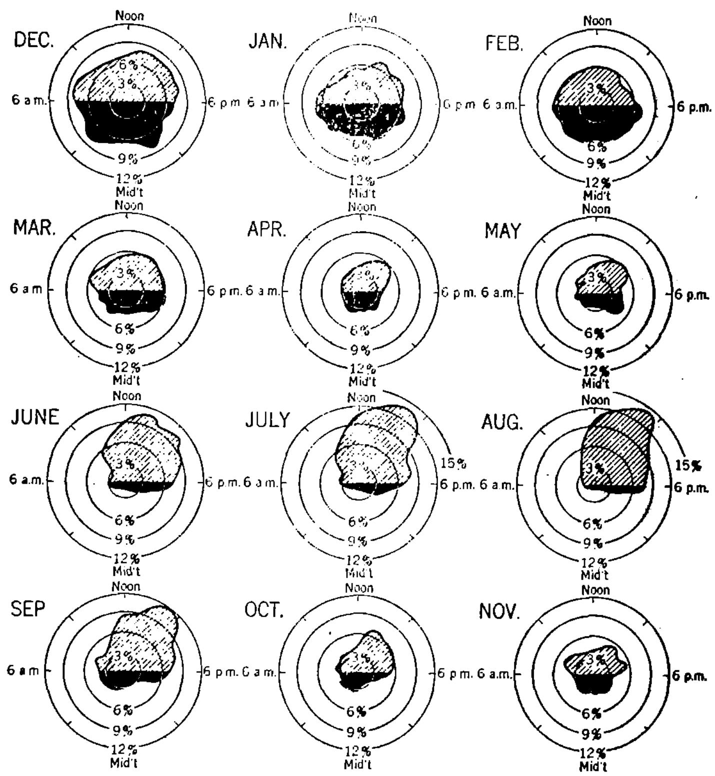

FIGURE 1.—Graphic representation of hourly percentage frequencies of measurable rains at New Orleans, La. (based on records for the 30 years, 1898–1927, inclusive). Circumference of each monthly circle represents the 24 hours of the day, noon at the top. Radial distance along any hour line represents the percentage of total hours of that name in which measurable rainfall occurred. Concentric circles indicate intervals of 3 per cent in frequency values. Areas embracing the interval from 6 p. m. to 6 a. m. (covering night hours) are blocked out in black

in the total of rainy hours in that month as compared with July and September.

The charts in Figure 1 afford a particular emphasis to the characteristic features of rainfall distribution throughout the day in all seasons, but that figure does not present to the eye a proper comparison of the relative *monthly* values of frequency, because values in that figure depend on radial distance—not upon area. April, for example, as compared with December, has about half as many hours with measured rain, but the comparative areas for April and December in Figure 1 are nearly as one to four.

TABLE 3.—*Summary of monthly frequency and mean intensity of hourly rainfall records (New Orleans, La., 1898–1927, inclusive)*

	January	February	March	April	May	June	July	August	September	October	November	December
Total number of hours with only a "trace" of precipitation	1,116	939	863	556	539	738	917	817	757	584	616	1,229
Gross percentage frequency,[1] N/T	5.0	4.6	3.9	2.6	2.4	3.4	4.1	3.7	3.5	2.6	2.8	5.5
Total number of hours with measurable precipitation (a)	1,322	1,213	1,128	850	861	1,046	1,252	1,118	1,159	849	843	1,665
Gross percentage frequency,[1] N/T	5.9	6.0	5.0	3.9	3.9	4.9	5.6	5.0	5.4	3.8	3.9	7.5
Combined percentage frequency	10.9	10.6	8.9	6.5	6.3	8.3	9.7	8.7	8.9	6.4	6.7	13.0
Total rainfall, 1898–1927, inclusive, inches (b)	121.36	126.53	146.98	164.01	142.82	159.45	196.96	171.04	166.98	103.25	85.79	153.87
Average hourly intensity of rainfall ("traces" excluded, and value=b/a)	.092	.114	.136	.193	.166	.153	.157	.153	.144	.122	1.02	.092

[1] Percentage frequency expresses the value of N/T, where T=total number of hours in the month, and N=total number of hours with rain.

Figure 2 was therefore prepared, based upon Table 3, in order to show the relative frequency of hourly rainfall, month to month. In this figure it may be seen that the winter months experience the more extended rains, and four months, April, May, October, and November, are of nearly uniform low standing in percentage of hours with rain.

However, when the total *amount* of precipitation in each month is divided by the total number of hours with measurable rain, it is found that in average rainfall *intensity*, April leads all the months of the year, notwithstanding a position as to normal monthly total of rain which is exceeded by four other months. December and January show the lowest hourly intensities, although neither is the driest month in the year, as three other months carry considerably smaller normals of total rainfall.

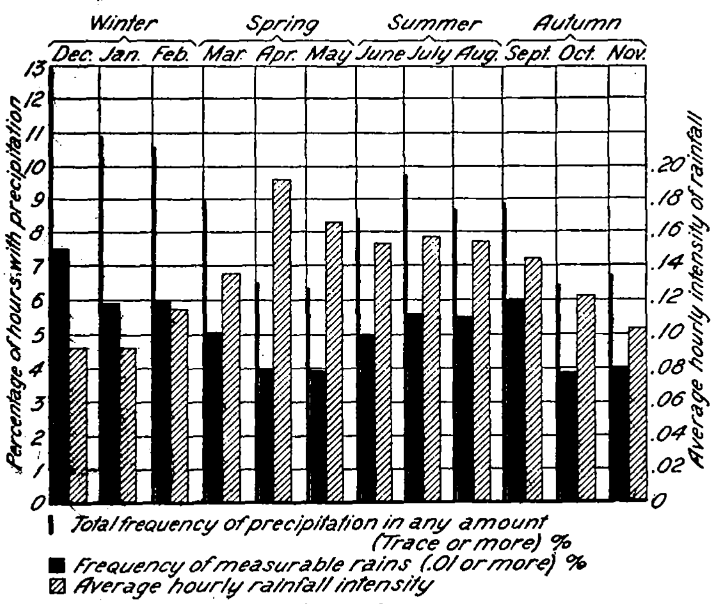

FIGURE 2.—Block chart of comparative monthly values, from 30 years precipitation records (1898–1927, inclusive) at New Orleans, La., combining the following in the order named: (1) Total percentage frequency of hourly precipitation of traces of rain and of measurable amounts. Thin black line. (2) Percentage frequency of hours with measurable rainfall. Heavy black column. (3) Average hourly intensity of measurable rains. Shaded columns. Scale for (1) and (2) at left, indicating percentage of total hours in a given month for 30 years, or "gross" frequency of occurrence. Scale for (3) at right, in hundredths of an inch per hour

These values evidently reflect variations in the character of the rainstorms at different seasons of the year. It is well known to residents of the middle Gulf coast region that the character of winter rains differs materially from the shower type prevalent in warmer seasons, but it is somewhat surprising to find the highest average intensity of rainfall in April (with normal precipitation 4.91 inches) rather than in July, when the normal precipitation total is almost one-third greater and thunderstorms the principal cause of rain.

The fortuitous character of the causes producing rains might be expected to tend (in a large number of random samples such as compose the 30-year record under consideration) towards intensity frequencies which might be classed in an orderly arrangement approximating the uniformity of a section of the "normal distribution curve." The smallest amounts of rain of course occur most frequently, and the largest amounts are most rare; it might therefore be expected that there is a fairly constant inverse ratio of intensity to frequency.

To test this idea the hourly records of measurable rain were grouped in classes, the first containing all

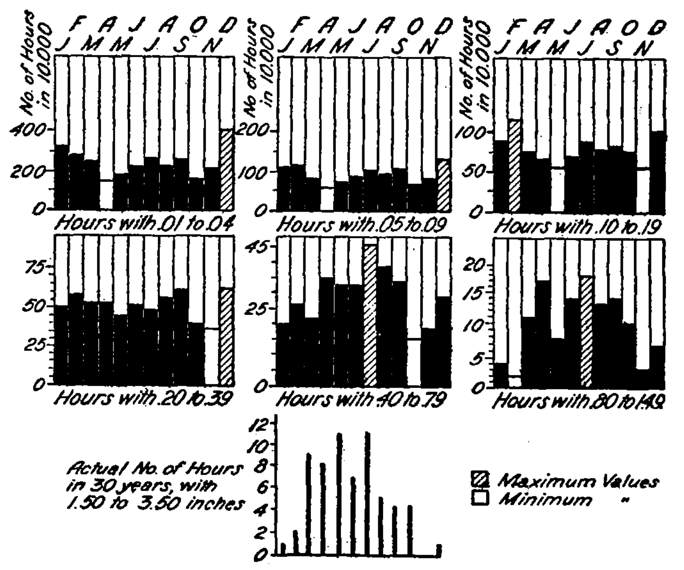

FIGURE 3.—Block chart of frequencies and approximate amounts of precipitation in various classes of hourly intensity, by months, as recorded at New Orleans, La., in the 30 years, 1898–1927, inclusive. Hourly intensity class limits shown under each group. Vertical scales at left indicate frequency of occurrence. Except for the bottom group, frequency is expressed as number of hours out of 10,000 (for each month) showing rainfall of given intensity. Vertical scales are expanded (successively doubled) in approximate ratio to the increasing values of successive group intensities. Length of column is therefore comparable, month to month and class to class, to show approximately the *total* amount of rainfall recorded as a result of each intensity

hours showing rainfall of 0.01 to 0.04 inch; the second, those hours with 0.05 to 0.09; the third, records of 0.10 to 0.19; the fourth 0.20 to 0.39; the fifth, 0.40 to 0.79; the sixth, 0.80 to 1.49; and the seventh and last, all amounts of 1.50 inch or over. The limits used for each class increase in approximate geometric ratio throughout the series. Each class after the first covers a range of amount about twice as wide as that of the preceding class.

Section I of Table 4 summarizes the count of these groupings for each month in the year, and, as in other tables, the frequency of each class is expressed (in Section II of Table 4) as a percentage of the total number of hours in the record for each month.

TABLE 4.—*Frequency of hourly rainfall intensities (random samples), classified in increasing values, Section I; relative to time totality, Section II; and also relative to total rainfall hours, Section III. (New Orleans, La., 1898–1927, inclusive)*

Month	(N) Total hours with precipitation of any amount (T or more), 1898–1927	SECTION I (C) Intensity group totals, 1898-1927								Average intensity over 1.50
		Trace	0.01 to 0.04	0.05 to 0.09	0.10 to 0.19	0.20 to 0.39	0.40 to 0.79	0.80 to 1.49	1.50 or over	
		Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	
January	2,438	1,116	727	232	199	110	44	9	1	1.62
February	2,152	939	589	223	224	117	53	5	2	1.58
March	1,991	863	575	185	167	119	49	24	9	1.61
April	1,406	556	353	117	145	116	75	36	8	2.17
May	1,400	539	400	142	119	99	73	17	11	1.95
June	1,784	738	502	180	146	109	72	30	7	1.83
July	2,169	917	592	210	192	106	103	38	11	1.74
August	1,935	817	505	197	171	124	87	29	5	1.75
September	1,916	757	532	213	169	132	77	32	4	1.82
October	1,433	584	394	146	163	87	34	21	4	1.88
November	1,459	616	453	148	115	81	39	7	0	------
December	2,894	1,229	933	298	220	134	63	16	1	2.14

Month	(T) Total hours in each month without regard to precipitation, 1898–1927, inclusive	SECTION II Gross frequency of occurrence, expressed as the percentage value of group totals (C) above, divided by the time totality (T), opposite (Group intensity values as above; column headings, Section I)								Remarks
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	
January	22,320	5.00	3.26	1.04	0.89	0.50	0.20	0.04	------	Percentage values for cases of hourly rains of 1.50 inches or over not given, due to very small number of such cases.
February	20,304	4.62	2.90	1.09	1.10	0.58	0.26	0.02	------	
March	22,320	3.87	2.58	0.83	0.75	0.53	0.22	0.11	------	
April	21,600	2.58	1.63	0.54	0.67	0.53	0.35	0.17	------	
May	22,320	2.42	1.79	0.64	0.53	0.45	0.33	0.08	------	
June	21,600	3.42	2.32	0.83	0.68	0.50	0.33	0.14	------	
July	22,320	4.12	2.65	0.94	0.86	0.48	0.46	0.18	------	
August	22,320	3.66	2.26	0.88	0.77	0.55	0.39	0.13	------	
September	21,600	3.54	2.46	0.99	0.78	0.60	0.34	0.14	------	
October	22,320	2.62	1.77	0.65	0.73	0.39	0.15	0.10	------	
November	21,600	2.85	2.10	0.69	0.53	0.37	0.18	0.03	------	
December	22,320	5.50	4.18	1.34	0.99	0.61	0.28	0.07	------	

Month	SECTION III Class frequencies relative to total hours with rain. (The hazard of occurrence of a given intensity among all the hours with rain. The figure below is the reciprocal of the value of C/N, in Section I, above, and should be read as "occurring in 1 hour out of" the number given below) (Group intensity values as above; column headings, Section I)								Remarks
January	2.2	3.3	10.5	12.2	22.2	55.5	271	2,438	The *smaller* the number in this table, the *higher* the frequency, which is the reciprocal of the number shown.
February	2.3	3.7	9.7	9.6	18.4	40.5	430	1,075	
March	2.2	3.3	10.3	11.4	16.0	39.0	80	212	
April	2.5	4.0	12.0	9.7	12.1	18.8	39	176	
May	2.6	3.5	9.9	11.8	14.2	19.2	82	127	
June	2.4	3.6	9.9	12.2	16.3	24.8	59	255	
July	2.4	3.7	10.3	11.3	20.5	21.0	57	197	
August	2.4	3.8	9.7	11.3	15.6	22.2	67	387	
September	2.5	3.6	9.0	11.3	14.5	24.9	60	480	
October	2.5	3.6	9.8	8.8	16.5	42.2	68	358	
November	2.4	3.2	9.9	12.7	18.0	57.4	208	------	
December	2.3	3.1	9.7	13.1	21.6	45.9	181	2,894	
GROUP AVERAGES									
Winter (November, December, January, and February)	2.3	3.3	9.9	11.8	20.2	45.0	242	2,230	
Summer (May, June, July, August, and September)	2.4	3.6	9.8	11.5	16.2	22.3	63	242	

Figure 3 represents the frequency in each class by a graphic scale, expressed as the number of hours out of 10,000, for each month, in which precipitation of each class range has occurred. The vertical scale on which frequency is plotted is doubled for each succeeding block after the first, in keeping with the increasing ratio of average intensities chosen as criteria for each succeeding group. This plan permits of comparison of frequencies in each class, month to month, and indirectly, from class to class.

Because the scale of hours bears a fairly close relation to the intensity of the precipitation, the height of each vertical block represents a reasonable approximation to the average amount of rainfall recorded in each class of intensities. Comparison reveals at once that notwithstanding the great frequency of hours with amounts less than 0.10 inch, the major portion of the total rainfall occurs in hours with somewhat higher rainfall intensities. Maxima of monthly frequencies for the lower classes occur in the winter months, up to and including the class with hourly amounts of 0.20 to 0.39 inch. The maxima shift to the warmer months for those classes which show higher intensities. Summer thundershowers evidently favor the production of hourly intensities of a half inch per hour or higher, and March, April, and May, are marked by a noticeable frequency of storms producing hourly intensities of 1.50 to 3.50 inches.

The largest random sample obtained in any single clock hour in the 30 years of record was 3.44 inches, in April, 1920. The highest amount in the 60 minutes of most intense rainfall, without regard to the hour lines on the record sheets, was 3.60 inches, April 9, 1920 (the same storm which produced the maximum random sample). Only two other cases of selected hour extremes exceed 3 inches for a single hour; one shows 3.01 inches in 60 minutes, April 18, 1914, and the other, 3.39 inches, April 16, 1927.

Higher rates are frequently recorded for fractional parts of an hour, but the cases quoted above cover the greatest intensities for whole hours of record at New Orleans. Random sampling (which is the true nature of the amounts recorded in the fixed hour brackets carried by the record sheets) thus reveals, in 30 years of measurements, a maximum hour value closely approximating the highest *selected* hour-intensity from the same rainfalls.

In the frequency studies so far described, the totality of elapsed time, including hours without as well as hours with rainfall, has been used as the base to which frequency was referred. The results measure what may be called the "absolute" or "gross" hazard of occurrence of rainfall, or of rainfall of a given intensity class.

The intervals *without* rain are thus involved in the values assigned to "gross" frequency, and the true nature of the hourly rainfall intensities in the average rainstorm, as it may show variation from winter to summer, or otherwise, is to that extent obscured. Scattered heavy rains such as those of April, for example, will show a sequence of rainfall intensity frequencies somewhat diluted by the great number of hours free from rain, as compared with a month such as December, which has more rainy and fewer dry hours.

To obviate this difficulty is simple. If the sum of all hours with the "rain condition" (as evidenced by records of a trace or more of precipitation) be taken as the base upon which a "relative" frequency for each group intensity is computed the results will display the true hazard of rainfall intensity amongst the hours in which rain actually falls. Seasonal comparison of the sequences of varying hourly intensities is then legitimate, and a truer view of the nature of the average rainstorm in each season is obtainable.

Section III of Table 4 sets forth numerical values for this "relative frequency" of intensity groups compared with total rainfall hours for each month of the year. The numbers used are set down in whole numbers instead of fractions, or percentages. Each value must be understood as indicating the average number of random samples of hourly rainfall which must be taken to secure one example of the given hourly intensity. A value of 4 for the group "0.01 to 0.04" in April, thus indicates that, in the average, hourly rainfall of 0.01 to 0.04 inch intensity occurs once in each four hours of rain in April. A value of 2,894, for hourly rains of 1.5 inches or over, in December, means that rainfall has exceeded 1.5 inches per hour in that month in only one hour out of nearly 3,000 with rain. The *smaller* values thus represent *higher* relative frequencies.

Casual inspection of the values in Section III of Table 4 reveals several noteworthy features. The uniformity of the frequency values in each of the first three intensity groups, considering together all months of the year in each group, is strikingly evident. Traces occur with a frequency range restricted to the small difference between 2.2 and 2.6, regardless of season. That is, considered solely in relation to hours with rain, about 40 per cent (the value of 1/2.5) of all rainy hours regardless of season, receive only a trace of rain. Compare this range of values with the percentage frequency of traces in the different months, relative to totality of hours in the month, shown in the "trace" column of Section II, Table 4, where the range of values is from 2.42 to 5.5, or a difference of somewhat more than 100 per cent of the lesser value. In other words, while traces of rain are actually experienced twice as frequently in December as in May, traces provide practically the same proportion of *rainfall* hours in either month, being actually less numerous in May because rainy hours of all other intensities are also less numerous in that month compared with December.

Similar considerations apply to the values for the next two intensity groups, 0.05 to 0.09 and 0.10 to 0.19, which occur with remarkably uniform *relative* frequency at all times of the year.

With the classes of hourly amounts between 0.20 and 0.39 inch, there appears a wider seasonal variation, and in the higher intensities this range increases to a very large ratio, until the last column carries values indicating that hourly amounts exceeding 1.5 inches or over are twenty times more frequent in May than in December. The value of "infinity" for this item in November is resultant from the fact that no case of intensity reaching 1.5 per hour was recorded in that month.

Further interesting and suggestive relations are brought out by studying the trend of frequencies through horizontal groups, that is, the frequency distribution through intensity series describing each particular month of the year. The numerical tables do not afford a suitably obvious display of such horizontal relations, and for that reason Figure 4 was devised to provide graphic representations and comparisons.

This figure is based upon a logarithmic scale of frequencies. The primary reason for using a logarithmic

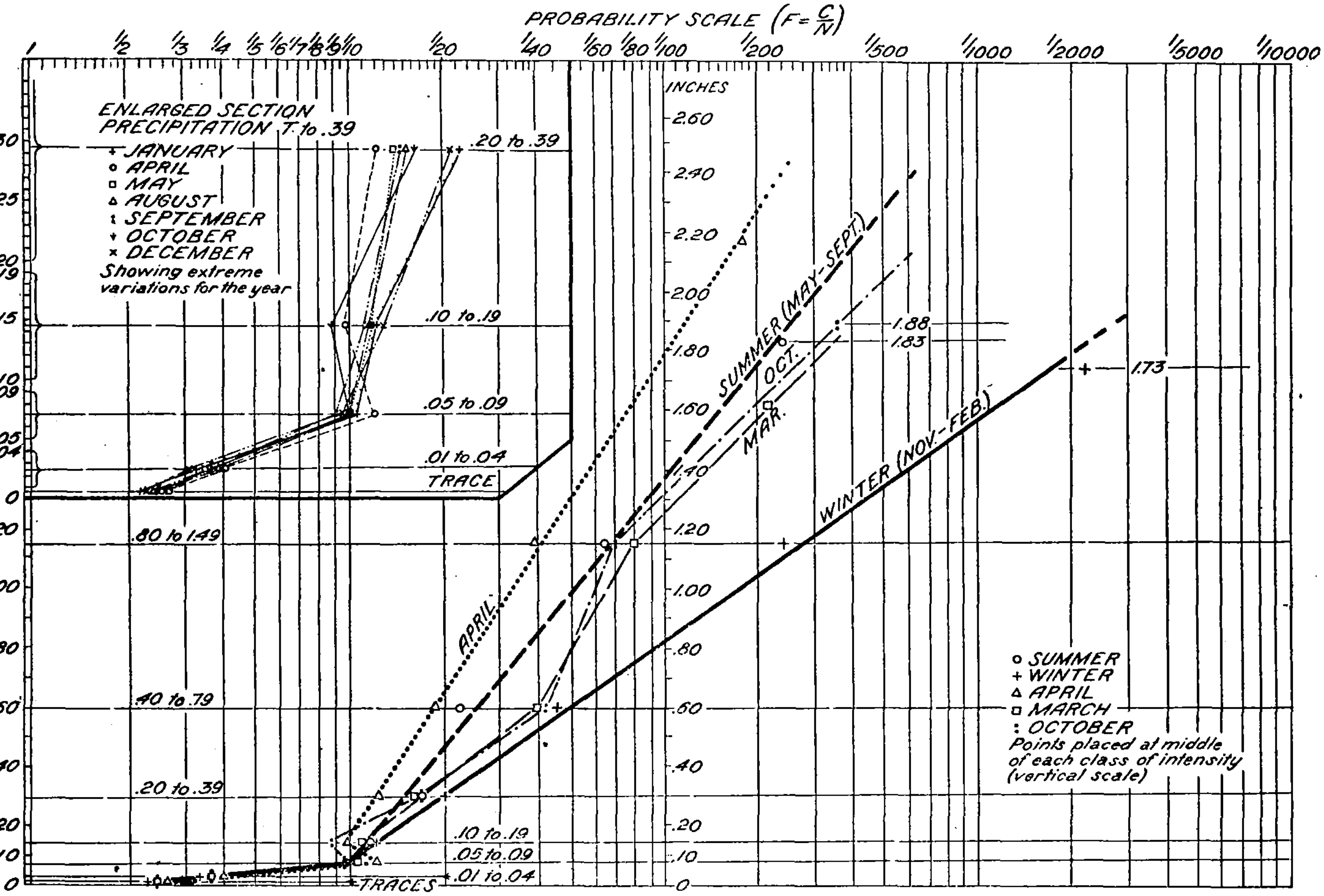

FIGURE 4.—Frequency of precipitation of varying hourly intensity, relative to the total of hours with rainfall of a trace or more, in each period, as shown by records at New Orleans, La., for 30 years, 1898–1927, inclusive. Each month or season is indicated by a curve connecting a series of points arising from relative frequency of each intensity in the month or season. Vertical scale shows values for hourly precipitation intensities in inches and hundredths. Horizontal scale carries frequency values in logarithmic series. Cross lines are placed at midpoint of each intensity class, as representing the approximate average value for each class. The frequency value indicated by vertical line intersecting intensity line at any plotted point expresses the average number of random samples of hourly precipitation required to secure 1 example of the intensity class for which the point is plotted. The fractional form is to be read as "1 example out of" the number in the denominator. Straight line relation of plotted points indicates that the values connected by that line are related as a logarithmic series

scale along the horizontal axis, on which frequencies are plotted, is to permit compression of that scale to convenient compass, without loss of detail in the smaller numbers. By no other means could a range of numbers from 2 to nearly 3,000 be plotted with clarity, meanwhile keeping within reasonable space limits.

The secondary, and as results show, the more valuable reason for the use of a logarithmic scale, rests in its important property of throwing into straight line relation, series of values varying by a fixed ratio, which would, under ordinary squared cross-sectional plotting, lie along a curved line. Straight lines and angles are more readily compared than curved lines.

Furthermore, when plotted values group themselves into straight line relations on a logarithmic scale this grouping is in itself evidence of a systematic internal structure in the group, the variation necessarily being in accord with a logarithmic ratio if it fits thus into logarithmic plotting. Straight line grouping of connected frequency values therefore warrants the inference that the events themselves are interrelated as a geometric progression, and are probably resultant from the operation of common causative influences which combine into multiplication patterns rather than the simpler and more heterogeneous patterns of addition. With these considerations in mind the nature of Fgure 4 may be better understood.

The figure is in two parts. A larger section gives representation to full series of hourly rainfall intensity-frequencies, from "traces" to the highest hourly amounts recorded. A smaller section, with the vertical scale expanded to four times its value in the larger, carries frequency-intensities of the lower groups, trace to 0.39 inch, only. The latter is made necessary by the merging of the similar values for these groups, when plotted on the relatively short scale of rainfall intensity used in the larger section. Even with the expanded vertical scale used in the enlarged section, the similarity of relative frequency values for groups of hourly intensity varying from "trace" to 0.09 inch is so great as to practically merge the lines for the several monthly series.

Perhaps the most interesting feature of these graphs is in the fact that the positions for many series of three to five group values, do approximate straight line relations. The frequency values for the low intensity groups not only form individual straight line series for three points, as stated above, but they *all* approximate the same straight line of values, up to amounts of a tenth of an inch of rainfall per hour.

Between 0.10 and 0.39 inch intensities there is a sharp common discontinuity in the frequency series. The rapid rate of decrease in frequencies (indicated by the low angle of the curve prior to that point) suddenly changes, or even in some cases, notably in the values for April and October, increases for frequency of occurrence of 0.10 to 0.19 inch amounts as compared with the number for the group, 0.05 to 0.09 inch.

Thereafter, above 0.19 inch, the series in the main resume satisfactory straight line relations, but with divergent angles of frequency for different seasons. The monthly series for winter (November to February, inclusive) and for summer (May to September, inclusive) were of such uniform trend (see Section III, Table 4) that these groups are represented on the major graph as *seasonal averages*, and not by individual monthly lines.

Slight smoothing of the positions is involved in applying straight lines to these average seasonal frequencies, but this procedure is believed to be justifiable in order to facilitate seasonal comparisons. Naturally, the angle of the winter series is below that for the summer series; this simply reemphasizes the fact already stated, that in winter, the character of the precipitation is such that the larger hourly rainfalls are less frequently recorded, and that in summer, when the convectional type of rain is prevalent, the higher rates of rainfall are more frequently recorded.

The line for April rains lies highest of all after rising above 0.10 inch intensity, and for *five intensity frequency positions, from 0.10 to 2.17 inches per hour, the points are almost exactly in true straight line logarithmic sequence.* The writer considers this a most noteworthy case of a group relation indicative of the operation of consistent underlying causative forces productive of the events so nicely interrelated.

In contrast to the consistency of the frequency curves for winter, summer, and for the month of April, is the irregular grouping of positions representing the frequency series for March and October. Both of these latter curves take a course at first more nearly parallel to the winter type, but, above 0.79 intensity, both rise to a slope more nearly like that for summer. The transitional character of these two months separating winter and summer conditions thus appears to be clear, and a mixture of seasonal influences seems evident in both.

The interesting relations and comparisons resultant from these "relative frequency" studies, just described, invite speculation as to the underlying causes which have produced two discontinuous intensity series in the hourly rainfall at New Orleans. One force or set of forces must have operated in the light intensity range, from trace to 0.10 inch, over which the monthly values agree in producing what amounts to a single line of frequency. Another, distinctly different, factor must come into play to produce the elevation in the angle of frequency lines through the upper range of intensities.

These differences should be explainable in terms of the meteorological processes commonly understood as at work in causing rainfall anywhere. While this problem is too complicated for full attention here, a tentative line of suggestive reasoning is offered.

Obviously, one set of causes operates with considerable relative uniformity regardless of season, to produce the more numerous low intensity samples of precipitation. Superimposed upon these are intensifying factors which begin to operate at rainfall rates of 0.10 inch per hour, and elevate the frequency of production of higher rates of rainfall. Whatever the nature of this second set of factors, it is more effectively at work in summer than in winter, with respect both to frequency and intensity of heavy rainfalls. It finds its highest stage of development in late spring, when the heaviest intensities are relatively most numerous.

It is universally agreed that the most active process of rainfall production is convectional overturning. Secondary to convection in this respect, are the other processes resulting in precipitation, such as the gradual forced elevation of warm air on sliding surfaces only slightly inclined to the horizontal, and cooling by mixture or by radiation.

The latter processes are inherently slow, and reveal none of the violent self-energizing quality that marks convectional overturning. The resultant rainfall must be equally deliberate in rate, and show a very high relative frequency of small amounts of hourly rainfall, with a rapid decrease in frequency for rates above the smallest. The upper limit of intensity of rainfall from nonconvectional causes would appear, from Figure 4, to rise but little if any above the order of a tenth of an inch per hour.

On the other hand, the limit of intensity of rainfall production from convectional overturning is less dependent on the rate of action in the elements of a process than upon the quantity and quality of the supply of warm, moist air and the degree of instability provided before the process begins. Convection is like a conflagration, in that once started it is able to support and extend itself far beyond the initial impulse, through a growth process limited only by factors competent to control the progressive conversion of latent energy into active work.

Small examples will be similar to large ones in that, up to the limit of the energy supply, the process is one of prompt growth from small beginning to maximum possible development. The large examples of convectional overturn may be supposed, in the course of development, to pass through stages of intensity that generally duplicate the characteristics of the smaller disturbances arising under the same seasoned conditions. The by-product of both would be rainfall of similar intensities up to the limits of the lesser disturbance. An intensity series resultant from a collection of samples of convections of all sizes should thus be harmonious within the general limits imposed by seasonal controls.

Colder air, in winter, will set a lower limit of convectional development than that generally obtainable in the warm, moist air of summer. Hence the winter curve of rainfall frequency and intensity lies lower than that for summer.

In the spring the still vigorous cyclonic exchange of polar and equatorial air combines with rapidly rising temperatures and an increasing moisture content of air masses warming near the earth's surface to offer opportunity for development of maximum instabilities. The season favors the conjunction of air currents of great contrast in temperature and humidity, which frequently results in a conversion of general cyclonic energy into the activity of local convections, with rainfall as one of the chief by-products. Thus arise the convectional disturbances of most energetic form, having the largest limits within which their growth can proceed, and thus the curve for April rises to a maximum relation of rainfall intensity to relative frequency.

The largest amounts of rainfall for 24-hour periods occur, at New Orleans, in spring rainstorms (between March and May), in which the quantity of precipitation exceeds even those heavy amounts produced by the passage of well developed tropical storms, which have been responsible for the most intense 24-hour rainfalls in the remainder of the year. The most notable example of the former class of storms is that of April 15–16, 1927, when 14.01 inches of precipitation occurred at New Orleans in one day's rain. The general characteristics of this type of rainstorm are worthy of further study, to place them into correct relation to the major movements of the atmosphere which must attend them.

METEOROLOGICAL SURVEY OF PROPOSED SITES FOR THE SAN FRANCISCO MUNICIPAL AIRPORT [1]

551.5: 725.39 (794)

By ERNEST E. EKLUND

[Author's abstract]

Many sites for the proposed San Francisco municipal airport were suggested and the merits of each were discussed at numerous hearings before the Board of Supervisors of the City and County of San Francisco. The opinions of experienced Government and civilian flyers were obtained, but they differed so widely, particularly as to weather conditions, that it was impossible to agree upon a site and it was therefore decided to develop a temporary airport, pending the results of a meteorological survey of all proposed sites, on which to base final judgment in selecting a site for the permanent airport. In cooperation with the city engineer's office, the Weather Bureau was asked to outline the survey and to supervise the work during its progress.

PHYSICAL REQUISITES OF AN AIRPORT

The three primary requisites of an airport are (1) favorable climatic conditions, (2) adequate size, and (3) accessibility. While nearness to the metropolis is desirable, this factor has little weight in determining the best possible location for an airport unless the two more important requirements, i. e., suitable climatic conditions and adequate size, have first been satisfied. The airport must be of sufficient size to provide for buildings and still leave ample room for the operation of aircraft. Runways must be oriented so that planes may take off or land into the wind and they must be sufficiently long to provide a safety factor in the operation of transport planes.

Important as size and nearness are to the problem of airport location, the basic physical requisite is meteorological suitability. Hazards due to weather must be reduced to the lowest possible minimum, which can only be done by choosing the location that has the most favorable meteorological conditions. All other considerations may therefore be disregarded if a proposed location for an airport is unfit for safe landing and scheduled flying because of meteorological unsuitability.

AVAILABILITY OF SITES MEETING REQUIREMENTS

No site within the city and county of San Francisco was suitable for development as an airport. With water to the west, north, and east, the search for sites was necessarily directed southward along the peninsula. Many possible sites were offered and six specific sites were chosen for consideration in the meteorological survey.

Site No. 2 is located just south of what is locally known as South San Francisco, and this location was favored by many because it is nearest to San Francisco. The selection of this location was opposed by others on the grounds that it is bordered by a high tension power line, that rough air is found there owing to the proximity of the San Bruno Mountains and that the site is frequently covered with fog.

Site No. 6 is located 1 mile south of site No. 2 and is the one selected for the temporary airport, known as Mills Field. Those in favor of this location claimed that it is far enough south to escape fog and unfavorable winds attributed to site No. 2 and that it is favorably situated with respect to obstructions. Opponents of this site claimed that more favorable weather conditions would be found still farther south.

Sites Nos. 1 and 4 lie immediately south of site No. 6 and may be considered together since they are separated by the highway only. Site No. 1 is obviously deficient

[1] Complete report, with tables and figures, is on file at Weather Bureau Office, San Francisco, Calif. It is expected that it will later be published in full as a public or private document.—E. E. E.